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Induced Secondary Combustion in Woodstoves

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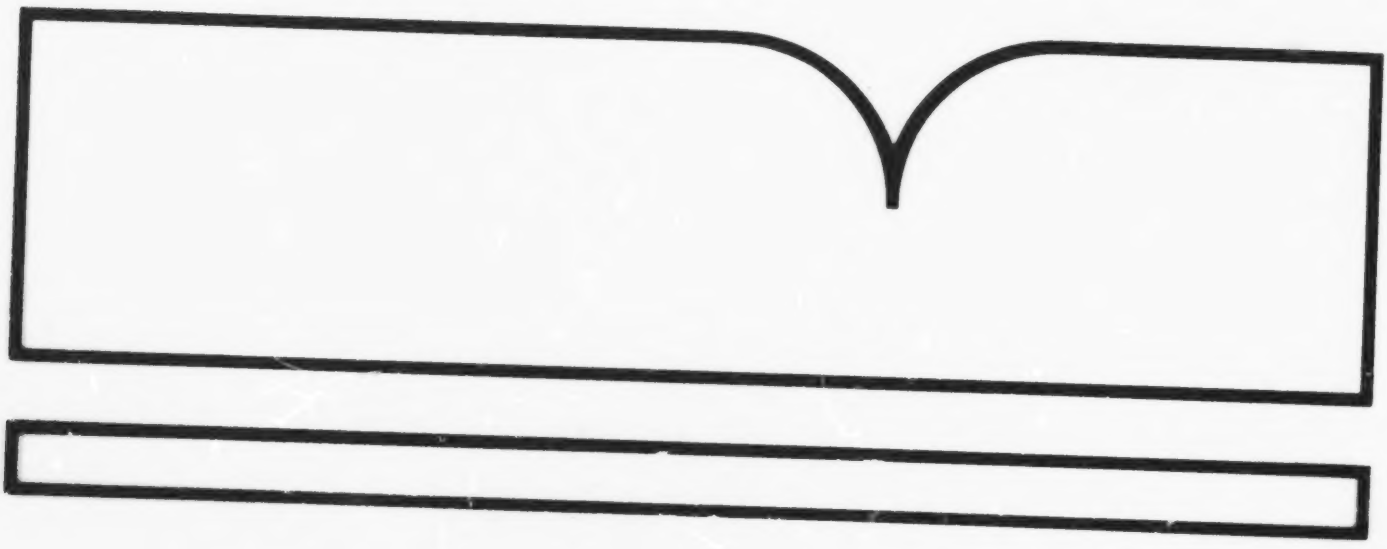

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16. ABSTRACT

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Wood	Woodstoves	11L
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ABSTRACT

This paper provides information useful for woodstove designers concerned with lowering emissions. A dual-chamber woodstove was modified to induce secondary combustion by utilizing an ignition source and forced flow of secondary air. The ignition source was an electric glow plug installed in the secondary chamber. The secondary airflow was maintained at preset flow rates and supply temperatures. Wood was burned in the stove in a laboratory following a standard protocol, and the stack emissions were continuously monitored. The modified stove generally emitted less pollution than the same stove did prior to modification. Emission levels generally declined as the flow rate of secondary air was increased and as the supply air temperature was increased. It is concluded that incorporation of these modifications into a woodstove, with appropriate controls, represents an effective emission control technology.

INTRODUCTION

The use of wood as a fuel for residential heating has increased dramatically in recent years. The concomitant increase in air pollution is well documented[1]. Airtight woodstoves in wide use today regulate heat output by throttling the air supply to the combustion chamber, producing fuel-rich conditions that commonly allow the exhaust of unburned combustibles when the stove is operated at low heating rates. More complete combustion is the design objective for new woodstoves, and many design alternatives have been evaluated. One of the most promising design concepts is the use of dual chambers within the woodstove. One chamber, the primary chamber, contains the burning wood and allows limited air entry to sustain a smoldering fire that volatilizes the combustibles. The combustible gases then pass into the secondary chamber, where combustion is completed with the aid of additional air. The advantage to this arrangement is that the rate of fuel volatilization is decoupled from the combustion process so that complete combustion can be achieved at low burn rates.

Sustaining combustion in the secondary chamber of a woodstove is difficult. As with all combustion, the combustibles and the air must be well mixed, the composition must be within flammability limits, and the temperature must be greater than the ignition temperature. In a woodstove, the volatilization rate and the chemical composition of the combustibles change throughout the burn cycle. The flow rate of secondary air, which is usually naturally aspirated, changes with the primary flow, as does the turbulence which causes mixing. The temperature in the secondary chamber changes as well. Stove design modifications that control these widely varying conditions could promote secondary combustion. These design factors include methods to sustain high temperature in the secondary chamber, to preheat the supply air to the secondary chamber, to regulate the gaseous composition, and the use of an ignition source in the secondary chamber[2]. The first three of these concepts have been tested in the laboratory to measure their effectiveness in reducing emissions[2,3,4]. In general, the emissions were somewhat reduced when the stove was burned at medium and high firing rates, but little or no emission reduction was observed at the low burn rates that are commonly used in homes.

Use of a natural gas pilot flame as an ignition source to sustain secondary combustion received limited testing[3]. Laboratory measurements of woodstove emissions demonstrated a substantial decrease during limited testing, but the experiment was suspended because of the practical problems associated with supplying an external natural gas source to a woodstove.

The effectiveness of using a more practial electric glow plug as an ignition souce, in combination with forced flow of secondary air, was measured in laboratory tests[4]. During those tests, wood was burned in a commercially available dual-chamber woodstove using three stove configurations: (1) the original configuration, (2) activation of an electric ignitor at the entrance to the secondary chamber, and (3) activation of an electric ignitor plus forced flow of secondary combustion air at the rate of 100 scfh (0.79 L/s). The stove was fired at low, medium, and high burn rates. At each burn rate, the average emissions of carbon monoxide (CO) decreased with the addition of the ignitor. The use of both the ignitor and the forced flow of secondary air, however, increased emissions from the original configuration. This finding was attributed to one or both of two factors: (1) the flow of secondary air was too great and forced the resultant combustible gas mixture outside of the flammability limits and/or (2) the secondary air was injected at a temperature that was too low and quenched the secondary combustion or prevented ignition by the ignitor. Due to the limited testing, it was impossible to identify which combination of secondary air flowrate and temperature, if any, would allow sustained secondary combustion.

This paper describes the results of tests designed to determine the relative importance of flowrate and temperature of secondary air in reducing woodstove emissions.

PROCEDURE

This study utilized a commercially available dual-chamber woodstove. This stove, shown schematically in Figure 1, utilizes an S-flow configuration to promote secondary combustion. During operation, wood is loaded into the primary chamber. A small fire burns in the primary chamber to heat the wood and volatilize the combustibles; the release rate is controlled by the amount of primary air introduced through a damper. The gaseous combustible products then pass through a narrow throat into the secondary chamber. Secondary air is introduced at the throat. Secondary combustion, if any, occurs in the secondary chamber. The combustion products then pass beneath the top of the stove to transfer heat prior to exhaust.

The basic stove was modified in two ways. (1) Two electric glow plugs were installed near the entrance to the secondary chamber. Each glow plug, similar to those used as ignitors in gas appliances, had a flat blade shape 0.5x2.0 in. (1.3x5.1 cm) that protruded into the gas stream. This ignitor drew 3.5 A. from the 120 VAC supply. (2) The secondary air supply was connected to a compressed air system, an in-line rotameter, and a variable power resistance

heater to regulate the flowrate and temperature (shown schematically in Figure 2).

The woodstove was installed and operated in an air-conditioned laboratory. The stove was mounted on a platform scale for monitoring the wood consumption rate. The exhaust pipe included an oil seal joint to "float" the stove from the building exhaust system.

The stove was instrumented to monitor performance and emissions. Three thermocouples were mounted in the gas stream passages, one each upstream and downstream of the secondary chamber, and another in the secondary air supply inlet. The rates of emission of CO and unburned hydrocarbons (HC) were continuously monitored by drawing samples at an elevation of 5 ft (1.5 m) above the stove top. The CO was measured with a nondispersive infrared sensor and the HC was measured with a flame ionization detector, supplied by a noncondensing heated line. Exhaust gas contents of O_2, N_2, and CO_2 were also continuously monitored. All data were recorded with a microcomputer-based data acquisition system that multiplexed all sensors at 1 minute intervals.

During testing, white oak cordwood was burned. Wood pieces were typically 12-14 in. (30-35 cm) long with hydraulic diameter of about 2 in. (5 cm). The wood moisture content was estimated to be 12-15%, but was not measured; moisture content was held constant by storing the wood in a controlled environment room. A typical test charge consisted of 3 - 4 pieces of wood weighing 7-8 lb (3-4 kg). The wood was placed on a bed of coals consisting of about 1-1.5 lb (0.5-1 kg) of the previous charge, so about 5-7 lb (2-3 kg) of wood was burned during each cycle. For the duration of the burn cycle, the damper controlling the flow of primary air remained stationary. The burn cycle was deemed complete when the firebox temperature returned to within about 25°F (14°C) of the starting temperature. Since testing concentrated on the first portion of the burn when volatile HC's dominated the fuel supply, the exact definition of the completion of the burn cycle was not critical. Rather, emphasis was placed on maintaining consistency of the beginning of each cycle. At the completion of each burn cycle, the gas sampling tubes were flushed and the samplers were recalibrated.

The stove was operated at constant conditions throughout a burn cycle. The stove was burned with three primary air damper settings: medium fire at 50% open, low fire at 25% open, and very low fire with the damper set at about 10% open (previously determined to be the minimum opening at which a fire could be maintained). At each condition, the burn cycle was repeated several times. Table I lists the burn rates and the number of replications at each.

The ignitor was turned on prior to the beginning of the burn cycle. The flowrate and temperature of the secondary combustion air was adjusted prior to the start of the burn and maintained for the duration of the burn. The flowrate was set at 30, 60, 100, or 150 scfh (0.24, 0.47, 0.79, or 1.18 L/s). The air temperature was set at 400°F, 700°F, or 1000°F (200°C, 370°C, or 540°C). At the 1000°F (540°C) setting, the heater capacity was inadequate to heat a flowrate of 150 scfh (1.18 L/s), so the flowrate was reduced to 120 scfh (0.94 L/s). The matrix of test conditions is listed in Table I.

Data processing reduced the large number of collected data to useful average values in a series of steps. The raw data as measured for each run was stored by the computer, so during the first data processing step the absolute time was corrected to relative time from the beginning of the run and the emissions were adjusted for dilution by using the measured O_2 content of the exhaust to correct to 0% O_2. The second pass calculated the emission rate averaged over a given run, as well as other factors such as actual secondary air temperature and indications of secondary combustion. The third data processing step then accessed the average results for all test runs, sorted by test conditions, calculated the averages for each set of conditions, and identified and deleted statistical outliers based on average emission rate.

RESULTS

A large number of test runs were completed, with 220 runs performed to date. This large data base was required to cover the full range of test conditions and to provide adequate replication to average out the inherent variability in woodstove performance. Some of these test runs were not usable because of equipment failures, primarily intermittent data gaps in the computer storage and malfunction of the oxygen analyzer. Other test runs were deleted because they were statistical outliers. After these runs were eliminated from the data pool, 178 usable test runs remained. In order to conserve space, only the averages for each set of conditions are reported in this paper; complete data are available from the authors.

The average CO emission rate is affected by each of the variables tested: burn rate, flowrate of secondary air, and temperature of secondary air; these results are summarized in Table I. As the burn rate increased, the CO emission rate decreased; this finding is consistent with that reported many times previously[1]. Also, the CO emissions were generally reduced by the addition of the electric ignitor and the forced flow of secondary air.

The effect that secondary air temperature has on emissions is illustrated in Figure 3, where the flowrate of

secondary air is included as a parameter. At low and medium burn rates, there is a general trend to reduce the emission with higher temperature. That trend is less obvious, however, at very low burn rates or at low burn rates but relatively high flowrates (100 to 150 scfh, 0.79 to 1.18 L/s). It is not at all clear why this behavior is observed, for one would expect more complete secondary combustion at higher temperatures for all burn rates.

The emission rates for the original woodstove are also indicated in Figure 3. It can be seen that the emissions from the modified stove are usually substantially lower with the addition of the ignitor and the forced flow of preheated secondary air. The only conditions that produced higher emissions from the modified stove were the low flowrate of low temperature air at medium burn rates. This result may reflect the fact that the original stove induced greater secondary air flow and preheated that air more than was being artificially maintained during these tests.

The effect of flowrate of secondary air on emissions is shown in Figure 4, with the temperature included as a parameter. As a general trend, the emissions reduce with greater flowrate, but again that trend is more obvious at medium and low burn rates than at very low burn rates. These results may reflect the need for a critical residence time within the secondary chamber to allow complete combustion to occur, and the higher flowrates tested may carry the combustibles through the secondary chamber too fast.

The variability in the results presented makes it difficult to identify a particular set of conditions, flowrate and temperature, that would consistently reduce emissions from the woodstove tested. Yet this step must be accomplished before the use of an ignitor and forced secondary flow can be incorporated into the feedback actuation for an advanced design woodstove. In an effort to identify some set of optimal (or, at least, workable) conditions, the conditions segregated previously were further averaged as shown in Figure 5. The temperature effect was averaged for the upper plot while the air flowrate effect was averaged for the lower. What these data indicate is that forced flow at any temperature or increased temperature at any flowrate act to reduce emission. However, there appears to be a point of diminishing returns in each case. An air flowrate greater than 60-80 scfh (0.47-0.63 L/s) does not lead to much reduction in emissions. Similarly, preheating the secondary air much above 700°F (370°C) does not appear to lower emissions. Hence, it appears that using 70 scfh (0.55 L/s) of 700°F (370 °C) secondary air, in conjunction with an electric ignitor, will produce a significant reduction of emissions over a wide range of burn rates.

The variability of woodstove performance cannot be

overstressed. This study relied on test replications to reduce the likelihood that the findings would be inconclusive. But all test programs are limited, and this one could not continue the testing indefinitely to determine whether the results presented here would, in fact, "hold still" when repeated a large number of times.

CONCLUSIONS

This study sought to identify the conditions required of the secondary air flow that would reduced emissions in a dual-chamber woodstove equipped with an electric ignitor. In general, higher flowrates and higher temperatures of secondary combustion air reduced the CO emissions, but this trend exhibited inconsistency when the stove was fired at very low burn rates. It appears that fixing the flowrate of secondary air at 70 scfh (0.55 L/s) and preheating to 700°F (370 °C) would provide a reasonable compromise of conditions that would reduce emissions over the widest range of conditions.

Table I. Test conditions and average emissions.

BURN RATE	TEMP (°F)	AIRFLOW (scfh)	NUMBER OF RUNS	CO EMIS (ppm/min)
Very Low	0	0	4	26500
Very Low	400	30	5	11000
Very Low	700	30	4	9700
Very Low	1000	30	4	19100
Very Low	400	60	5	11700
Very Low	700	60	5	5100
Very Low	1000	60	4	11300
Very Low	400	100	5	11000
Very Low	700	100	5	9900
Very Low	1000	100	5	11400
Very Low	400	150	4	9900
Very Low	700	150	4	9900
Very Low	1000	120	4	7100
Low	0	0	6	18800
Low	400	30	4	17900
Low	700	30	4	11000
Low	1000	30	5	9400
Low	400	60	4	11400
Low	700	60	5	7600
Low	1000	60	7	4300
Low	400	100	5	11100
Low	700	100	5	5700
Low	1000	100	4	5900
Low	400	150	3	4500
Low	700	150	4	4200
Low	1000	120	5	9500
Medium	0	0	7	9500
Medium	400	30	6	14000
Medium	700	30	5	7100
Medium	1000	30	4	5000
Medium	400	60	5	8500
Medium	700	60	4	3500
Medium	1000	60	4	3800
Medium	400	100	5	6600
Medium	700	100	5	3900
Medium	1000	100	5	2100

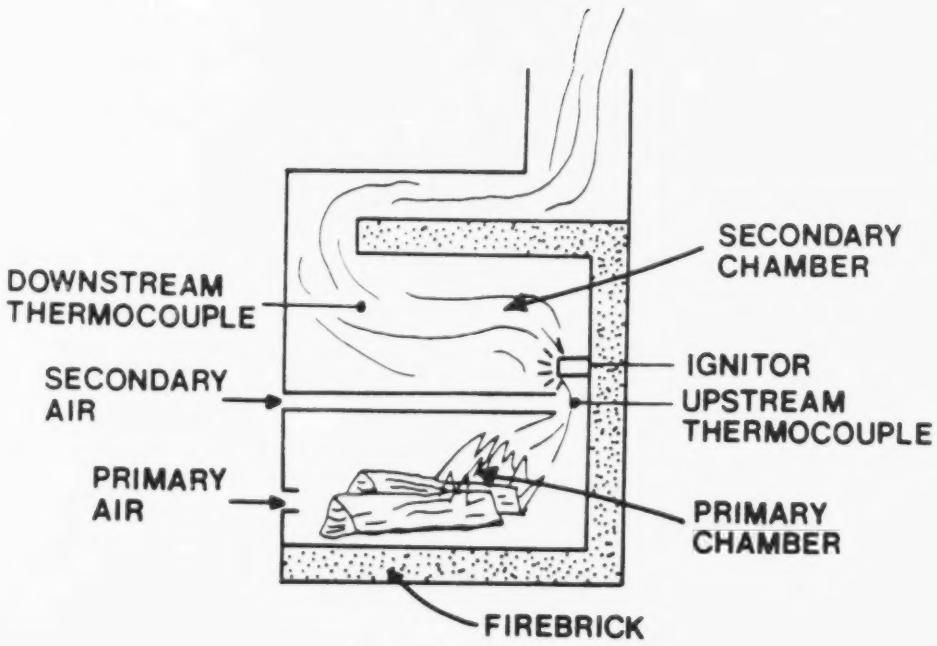

Figure 1. Schematic of modified woodstove.

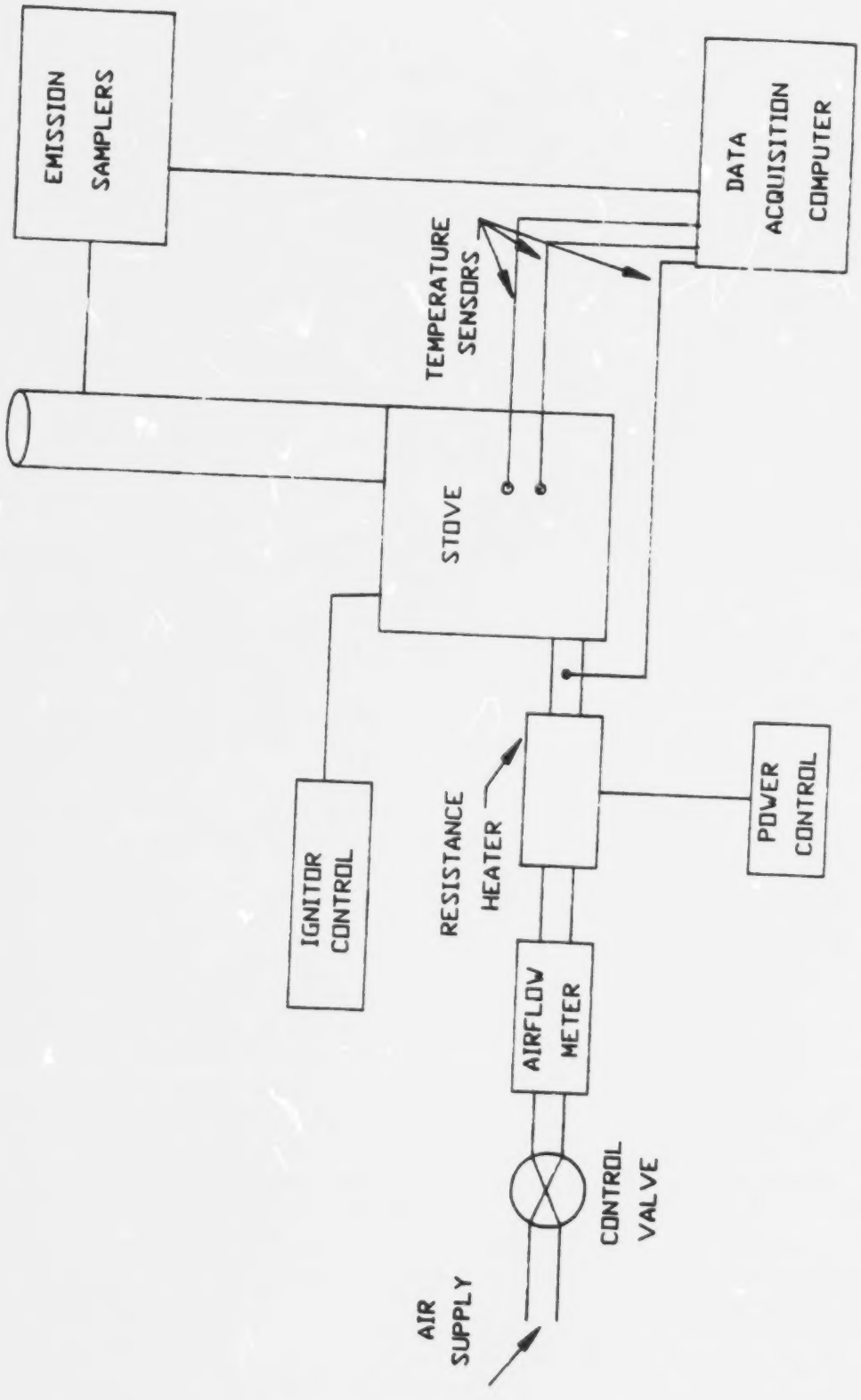

Figure 2. Schematic of instrumentation.

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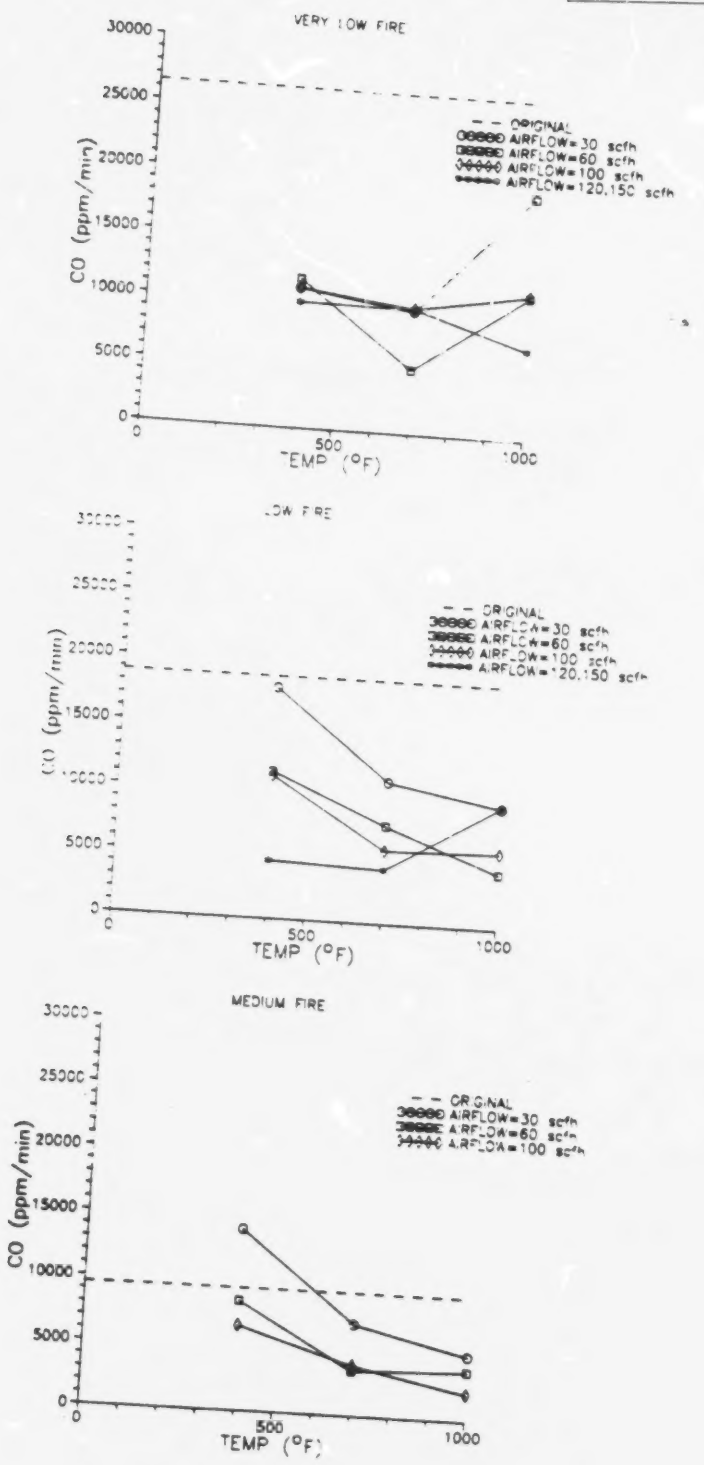


Figure 3. Effect of supply temperature on emissions.

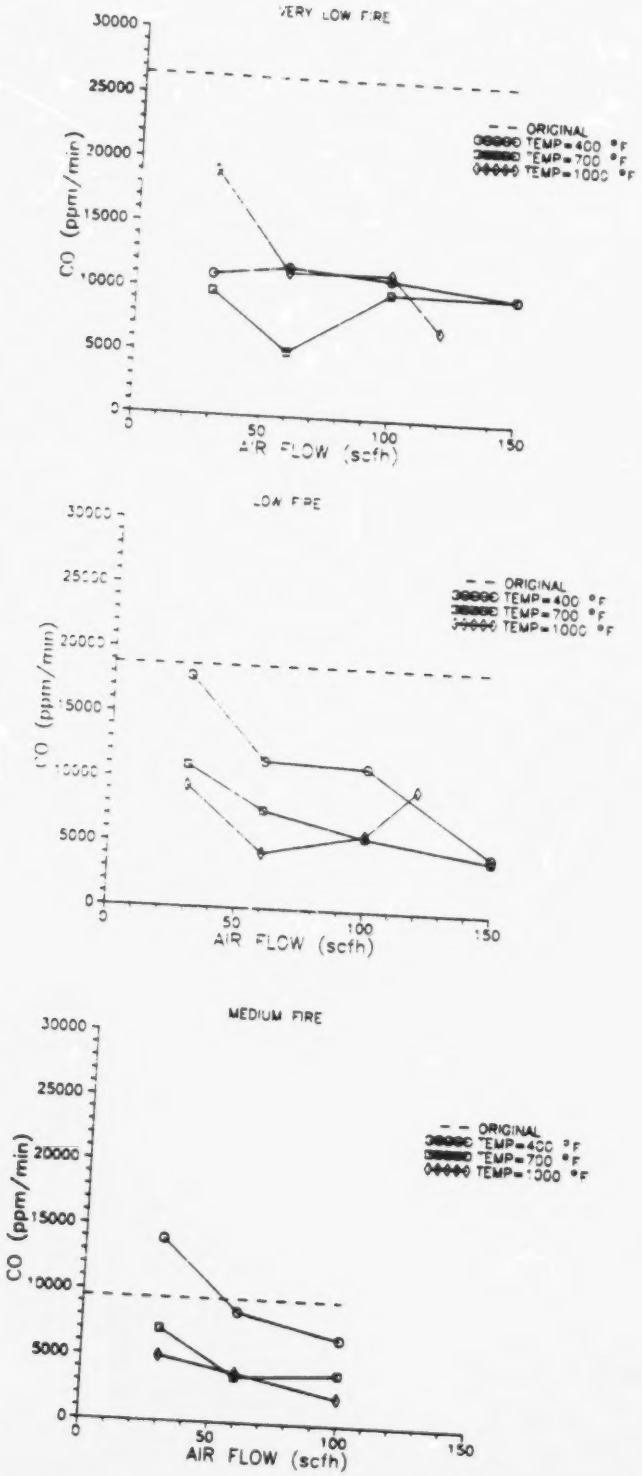
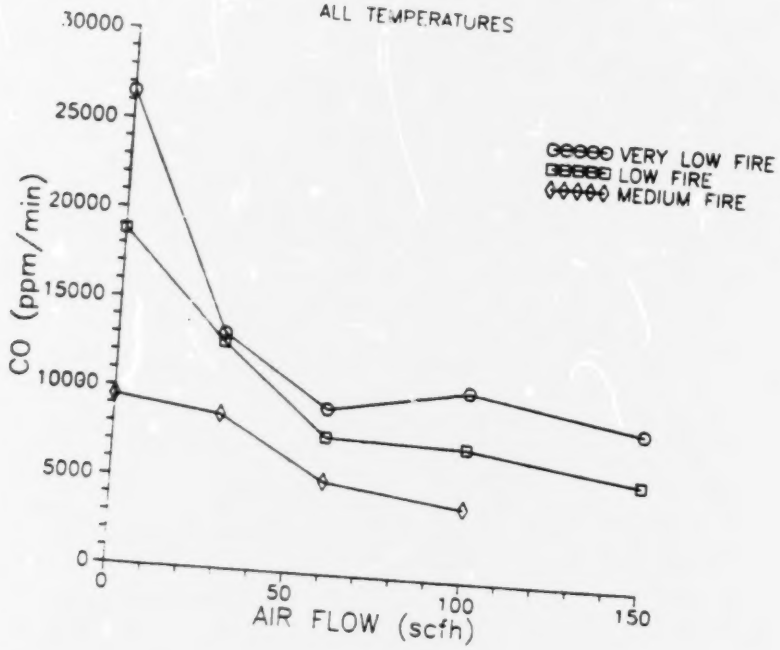


Figure 4. Effect of secondary air flow rate on emissions.



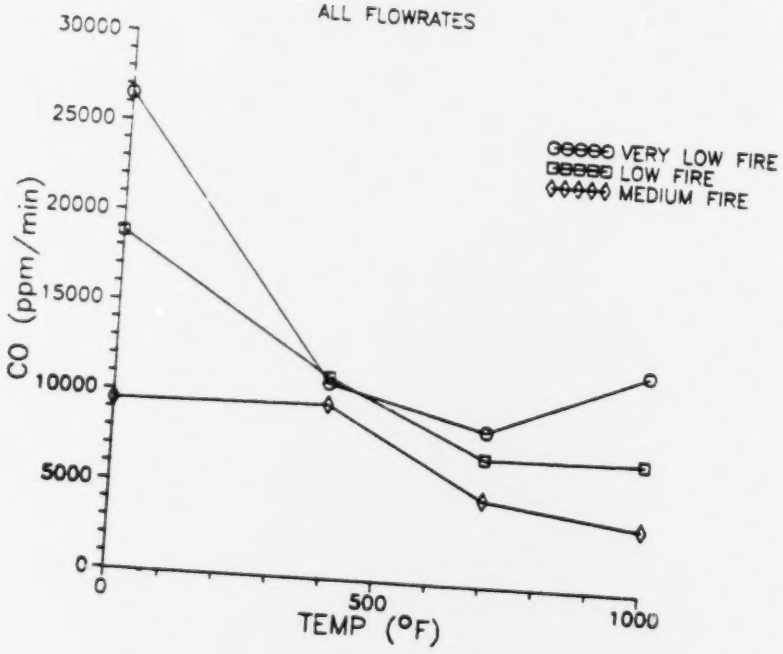


Figure 5. Average effects of air flow rate and supply temperature on emissions.

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